Working Memory in Spatial Knowledge Acquisition: Differences in Encoding Processes and Sense of Direction

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Summary: This study examined how different components of working memory are involved in spatial knowledge acquisition for good and poor sense-of-direction (SOD) people. We employed a dual-task method, and asked participants to learn routes from videos with verbal, visual and spatial interference tasks and without any interference. Results showed that participants with a good SOD encoded landmarks and routes verbally and spatially, and integrated knowledge about them into survey knowledge with the support of all three components of working memory. In contrast, participants with a poor SOD encoded landmarks only verbally, and tended to rely on the visual component of working memory in the processing of route knowledge. Based on the results, a possible model for explaining the differences in spatial knowledge acquisition and SOD was proposed. Copyright © 2010 John Wiley & Sons, Ltd.

People earn about surrounding environments and apply the knowledge to various wayfinding and navigation problems in their daily lives. For example, after moving into a new place, people learn the routes from home to work, school or shopping, and the spatial layout of the neighbourhood. During the process of acquiring such knowledge, information from the senses is filtered, abstracted, integrated, and then stored in long-term memory, a learning process called spatial knowledge acquisition.

Researchers discussed that spatial knowledge is classified into three types: landmark knowledge (knowledge about discrete objects or scenes), route knowledge (sequences of landmarks and associated decisions) and survey knowledge (configurational, map-like knowledge) (Siegel & White, 1975). In survey knowledge, landmarks and routes are interrelated with each other, and the distances and directions between them, even those not directly travelled, are available. The acquisition of survey knowledge is considered a sophisticated step in development, because in large-scale spaces the layout of landmarks and routes cannot be grasped from a single vantage point and its understanding requires mental layout of landmarks and routes cannot be grasped from a single vantage point and its understanding requires mental

Concerning survey knowledge, research showed, for example, that people acquired survey knowledge from various ways such as landmarks, routes, and the layout of the environment. Concerning route knowledge, research showed that people learned routes by verbally describing them (Gwinn, Fernando, James, & Wilson, 2002; Pazzaglia & De Beni, 2001), and also used landmarks spatially to update their positions or to estimate distances and directions (Blajenkova, Motes, & Kožhevnikov, 2005; Gwinn et al., 2002). These studies suggested that the verbal and spatial components of working memory are involved in the acquisition of landmark knowledge; but the role of the visual component has not been studied in detail thus far.

Concerning route knowledge, research showed that people learned routes by verbally describing them (Deyzac, Logie, & Denis, 2006; Meilinger, Knauff, & Bülthoff, 2008), or by visually recognising them, or by spatially interrelating them to update self-positions (Aginsky, Harris, Rensink, & Beusmans, 1997). These studies suggested that the verbal, visual and spatial components of working memory are all involved; but at the same time, the use of the spatial component was shown to be related to the tendency to understand routes in a survey (or two-dimensional) manner (Aginsky et al., 1997).

Concerning survey knowledge, research showed, for example, that people acquired survey knowledge from...
verbal descriptions of spatial relationships between landmarks and routes (Deyzac et al., 2006). In map learning, albeit different from the topic of this study, it was shown that people processed locational information in the visuospatial sketchpad (Coluccia, 2008; Coluccia, Bosco, & Brandimonte, 2007). But it remains to be answered how different components of working memory are involved in the acquisition of survey knowledge, which is characterised particularly by large individual differences.

As a measure of individual differences in spatial cognition, self-report sense of direction (SOD) has been widely used, and its validity demonstrated (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002; Kozlowski & Bryant, 1977). For example, people with a better SOD tend to do better on ‘survey tasks’ that require configurational understanding of environments (Hegarty et al., 2002), which maps onto the distinction between landmark- or route-based versus survey-type navigational tendencies (Pazzaglia & De Beni, 2001). The present research addresses these differences in spatial cognition from a perspective of differences in information processing in working memory: People with a good and poor SOD may acquire, or encode, knowledge about spaces differently, resulting in differences in internal representations of the acquired knowledge.

Two past studies specifically examined the relationship between working memory and the acquisition of knowledge about large-scale spaces (Garden, Cornoldi, & Logie, 2002; Meilinger et al., 2008). Garden et al. (2002) asked participants to learn two routes in a European city with concurrent articulatory-suppression and spatial-tapping tasks, and then to follow the learned routes again. They also examined participants’ spatial aptitudes in terms of whether they used survey (map-like) navigational strategies. Results showed that survey-type participants’ performance was disrupted by the spatial concurrent task, whereas non-survey participants’ performance was disrupted by the verbal task. These results suggest that the verbal and spatial components of working memory may be involved in the acquisition of landmark and route knowledge differently for good- and poor-SOD people. In their study, however, the role of the visual component of working memory and the acquisition of survey knowledge were not examined.

Meilinger et al. (2008) asked participants to learn two routes in a virtual environment with a concurrent verbal, visual or spatial task, and then to follow the learned routes again. Participants’ performance was disrupted by the verbal and spatial concurrent tasks, but not by the visual task, suggesting that verbal and spatial components of working memory are involved in the acquisition of landmark and route knowledge differently for good- and poor-SOD people. In their study, however, they did not preclude the possibility that the verbal and spatial concurrent tasks were more demanding than the visual task. Also, in the study, neither the acquisition of survey knowledge nor participants’ SOD was examined.

Based on these research backgrounds, this study aims to examine how the three components of working memory are involved in the acquisition of the three distinct types of spatial knowledge, in relation to people’s SOD. To do that, we used a dual-task method: participants learned routes with concurrent tasks (verbal, visual and spatial interference conditions) and without a concurrent task (a control condition), and then were tested on their landmark, route and survey knowledge. We examined whether participants’ performance on these spatial tasks decrease in the three interference conditions, to see which components of working memory are involved in knowledge acquisition. In particular, we aimed to reveal the roles of spatial versus visual components of working memory for good- and poor-SOD people. If the high cognitive demand for the acquisition of survey knowledge stems from the requirement of advanced spatial processing, it would be shown that poor-SOD people, who have difficulty with survey understanding, lack spatial processing of information about space. Also, even when the visuospatial sketchpad is found to be involved in spatial knowledge acquisition, the visual (not spatial) subcomponent would play a greater role for poor-SOD people than for good-SOD people, because of the lack of spatial processing by poor-SOD people.

METHOD

Participants

Thirty-two college students (14 men and 18 women) participated in the experiment. They were Chinese students at the University of Tokyo, and received monetary compensation in return for their participation. They had lived in Japan for 3 months to 2 years, and had no prior experience with the study area.

Materials

Route videos

Views along five routes in the downtown Tokyo area were videotaped from a car, and shown to participants as experimental stimuli. A video camera was set on a tripod that was fixed onto the passenger seat, with the horizontal visual angle 44° and the vertical 34°. The five routes were 2.3, 2.4, 2.3, 1.9 and 1.7 km in length, and had 4, 5, 4, 5 and 4 turns, respectively (Figure 1). The videos were 5 minute long each, and scenes for temporary stops were edited out. One video was used for task explanation and practice, and the other four were used in the learning phase for the main experiment. As an example, a snapshot view from one video is shown in Figure 2.

Concurrent tasks

Participants learned three routes with a concurrent interference task, and one route without any interference. We used three types of interference tasks (verbal, visual and spatial tasks), by modifying the tasks used in the Meilinger et al. (2008) study. Inter-stimulus intervals of these interference tasks were set a priori based on results from the practice phase (details below).

In the verbal interference condition, participants performed a lexical-decision task, in which they responded orally whether a combination of two syllables is a Chinese word. We used 310 frequent Chinese words and 310 non-words for this task. Non-words were constructed by randomising characters of Chinese words, with the ones that sound similarly to words being excluded. The words and
non-words were read by a 24-year-old female Chinese student, who was born in the northern part of China and speaks native Mandarin. Mean length was 701.03 ms (SD = 2.35 ms) for words and 700.57 ms (SD = 1.82 ms) for non-words, with no significant difference between the two.

In the visual interference condition, participants were given a time (e.g. 10:15) orally, and asked to imagine a clock with watch hands. Then they were asked to answer orally whether both the long and short watch hands pointed to the same half, when the clock face was divided into upper and lower halves. The times were randomly generated from combinations of 1–12 hours and 5–55 minutes, and were read by the same student who read the verbal stimuli. Meilinger et al. (2008) discussed that although this task might not load on an isolated system, it put much more load on the visual than on the spatial subsystem of visuospatial working memory.

In the spatial interference condition, participants heard a beep sound, transmitted randomly from one of three loudspeakers located 90 cm away to the left, to the right, and in the front of the participant’s seat. Participants orally indicated the direction in which the sound came.

**Observed variables**

We observed participants’ performance on (a) a scene-recognition task, (b) a route-choice task and (c) a map-sketching task, which were designed respectively to assess their landmark, route and survey knowledge. No time limit was imposed on any task.

In the scene-recognition task, participants were shown 24 photographs, and asked to indicate whether the photographs had been taken on the learned routes. Half the photographs were views from the learned routes, and the other half were distracters. In the route-choice task, participants were shown six views near intersections on the learned routes, and asked to indicate to which direction they had turned when they learned the routes. In the map-sketching task, participants drew maps of the learned routes in as much detail as possible, on a blank A4 sheet of paper.

**Attentional-demand control**

Before the learning phase, we included a control phase in which we adjusted attentional demands of the three interference tasks (Fernandes & Moscovitch, 2002). In this
phase, we asked participants to conduct the verbal, visual and spatial interference tasks with a continuous-reaction task, and measured reaction times on the continuous-reaction task. In the continuous-reaction task, four black-bordered boxes were presented horizontally on a screen, and a small black square appeared randomly in one of the boxes. Participants indicated in which box a square appeared, by pressing one of the keys correspondingly arranged on a keyboard, as quickly and accurately as possible. This phase was repeated several times (three on average), and the inter-stimulus intervals of the three interference tasks were adjusted so that the reaction times on the continuous-reaction task reached the same level.

**Procedure**

Participants were tested individually in a soundproof chamber, seated on a chair positioned 90 cm away from a 1018 x 760 mm screen onto which visual stimuli were projected. First, participants practiced the three interference tasks and the continuous-reaction task, and then began the attentional-demand control phase. After the control phase, participants viewed a practice video and experienced learning a route shown in the video, and were explained about the experimental tasks. They were instructed to study the routes by paying as much attention as possible, so that they could answer questions about the routes to be asked later. Then, participants learned the first video with or without a concurrent task (they viewed the video once for each route), and conducted the map-sketching, scene-recognition and route-choice tasks in this order (during these spatial tasks, participants conducted no concurrent tasks). After finishing the tasks for the first route, participants took a short break (varying in length from 1 to 5 minutes, according to participants’ requests), and proceeded to the second route. They repeated this process for a total of four routes. The allocation of the four conditions of the learning phase (the verbal, visual and spatial interference conditions and the control condition) to the four routes and the order of viewing the four routes were randomised across participants.

After finishing all tasks, participants filled out a questionnaire about SOD. We used the Santa Barbara Sense-of-Direction (SBSOD) scale (Hegarty et al., 2002), and included six additional questions (shown in the Appendix) to assess participants’ strategies and tendencies in navigation in more detail. The experiment took 100 minutes on average.

**RESULTS**

**Sense of direction**

We divided participants into two groups based on their self-report SOD. To do that, we factor analysed their scores on the SBSOD scale, and extracted three factors labelled SOD, self-confidence, and navigational tendencies. We then computed mean ratings for 10 items that loaded on the SOD factor with a loading of greater than 0.2 (Questions 1, 4, 6, 7, 8, 9, 12, 13, 14 and 15 in the original SBSOD scale), and applied a median split (Mdn = 4.9) to create a good-SOD group (n = 16, M = 5.5) and a poor-SOD group (n = 16, M = 3.1).

**Scene-recognition task**

We examined participants’ performance on scene recognition in terms of the percentage of correct answers (an angular transformation was applied for analysis), and compared performance in the three interference conditions to that in the control condition (Table 1). An α-level of .05 was used for all statistical tests. For the good-SOD group, performance decreased significantly in the verbal and spatial interference conditions, t(15) = 2.68, p < .05; and t(15) = 3.33, p < .01, respectively. For the poor-SOD group, performance decreased significantly in the verbal interference condition, t(15) = 2.97, p < .01. There was not a significant difference in performance between the good- and poor-SOD groups in the control condition. Participants’ performance was above chance level (.50) in all conditions for both the good- and poor-SOD groups.

**Route-choice task**

We compared participants’ performance on route choice in the three interference conditions to that in the control condition, in terms of the percentage of correct answers through angular transformation (Table 1). For the good-SOD group, performance decreased significantly in the verbal and spatial interference conditions, t(15) = 2.55 and 2.28, respectively, p < .05. For the poor-SOD group, performance decreased in the verbal, visual and spatial interference conditions, t(15) = 3.41, p < .01; t(15) = 3.19, p < .01; and t(15) = 2.30, p < .05, respectively. There was not a significant difference in performance between the good- and poor-SOD groups in the control condition. Participants’ performance was above chance level (.33), except in the spatial interference condition for the good-SOD group and in the verbal and visual interference conditions for the poor-SOD group.

**Map-sketching task**

We analysed the accuracy of participants’ sketch maps in terms of whether the directions of turns were drawn correct. Table 1. Mean percentages (and standard deviations) of correct answers in the scene-recognition and route-choice tasks for good- and poor-SOD groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Control</th>
<th>Verbal</th>
<th>Visual</th>
<th>Spatial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scene-recognition task</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good SOD</td>
<td>.77 (.13)</td>
<td>.67 (.12)</td>
<td>.72 (.09)</td>
<td>.68 (.12)**</td>
</tr>
<tr>
<td>Poor SOD</td>
<td>.74 (.09)</td>
<td>.64 (.07)**</td>
<td>.68 (.11)</td>
<td>.70 (.09)</td>
</tr>
<tr>
<td><strong>Route-choice task</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good SOD</td>
<td>.72 (.32)</td>
<td>.48 (.23)**</td>
<td>.58 (.16)</td>
<td>.49 (.25)**</td>
</tr>
<tr>
<td>Poor SOD</td>
<td>.64 (.23)</td>
<td>.40 (.19)**</td>
<td>.37 (.21)**</td>
<td>.47 (.17)**</td>
</tr>
</tbody>
</table>

*Note: For each task, participants’ performance in the verbal, visual and spatial interference conditions were compared to that in the control condition, within good- and poor-SOD groups. 
*p < .05; **p < .01.*
correctly. The numbers of sketch maps on which all turns were depicted correctly are shown in Table 2 (examples of sketch maps in Figure 3). For the good-SOD group, there was a significant difference in performance among the four conditions (Fisher’s exact test, $p < .05$), showing that participants did worse in the three interference conditions than in the control condition. For the poor-SOD group, there was not a significant difference in performance among the four conditions. In the control condition, a larger number of participants drew sketch maps correctly in the good-SOD group than in the poor-SOD group (Fisher’s exact test, $p < .05$).

We also examined the proportion of correct turns drawn on each participant’s sketch map (Table 2), and obtained the same patterns of differences between the control and the three interference conditions. Performance by the good-SOD group was worse in the verbal, visual and spatial interference conditions than in the control condition, $t(15) = 2.31, p < .05$; $t(15) = 2.78, p < .05$; and $t(15) = 3.82, p < .01$, respectively. For the poor-SOD group, there was not a significant difference in performance between the control and the interference conditions. In the control condition, there was a marginally significant difference in performance between the good- and poor-SOD groups, with the former outperforming the latter, $t(30) = 1.76, p < .10$.

### Attentional-demand control

There was not a significant difference in participants’ response times on the continuous-reaction task among the three interference conditions, showing that the attentional demands of the three interference tasks were controlled to an equivalent level (Table 3). Also, the percentages of correct responses to the three interference tasks were above 90%, indicating that participants paid enough attention to these tasks.

### Additional questions about sense of direction

To examine individual differences in strategies and tendencies in navigation in detail, we calculated the correlations between participants’ responses to the six additional questions (Appendix) and mean ratings for the items loading on the SOD factor (Table 4). Significant correlations were observed for Questions 16 ('I can usually memorize a place even if I have been there only once'), 19 ('I am very good at learning the layout of an environment') and 21 ('I usually envision a two-dimensional map in mind when learning a novel route'), corroborating the tendency of survey understanding by good SOD people.

### DISCUSSION

This study examined how people with a good and poor SOD differ in the use of different components of working memory to encode different types of spatial knowledge. From a dual-task approach with the attentional demands of interference tasks being controlled, we obtained results that showed important differences between these two groups of people. We now discuss them in terms of the roles of verbal, visual

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**Table 2. Numbers of correct sketch maps and proportions of correct turns drawn by participants in the good- and poor-SOD groups**

<table>
<thead>
<tr>
<th>Learning condition</th>
<th>Group</th>
<th>Control</th>
<th>Verbal</th>
<th>Visual</th>
<th>Spatial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of correct sketch maps</td>
<td>Good SOD</td>
<td>11</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Poor SOD</td>
<td>5</td>
<td>2</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Proportion of correct turns</td>
<td>Good SOD</td>
<td>.88 (.27)</td>
<td>.53 (.41)*</td>
<td>.57 (.41)*</td>
<td>.55 (.39)**</td>
</tr>
<tr>
<td></td>
<td>Poor SOD</td>
<td>.69 (.33)</td>
<td>.51 (.31)</td>
<td>.75 (.35)</td>
<td>.55 (.37)</td>
</tr>
</tbody>
</table>

*p < .05; **p < .01.

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Figure 3. Sketch maps drawn by four different participants. (A), (B), (C) and (D) were sketch maps drawn for Routes (B), (C), (D) and (E) in Figure 1, respectively.
and spatial components of working memory in the acquisition of landmark, route and survey knowledge.

**Working memory in the acquisition of landmark knowledge**

On the scene-recognition task, good-SOD people did poorly when they were verbally or spatially disrupted, showing that the verbal and spatial components of working memory are involved in the acquisition of landmark knowledge. That is, people with a good SOD encode knowledge about landmarks verbally and spatially.

It is of interest that although information of the environment is inputted through the senses, people can process it verbally. Past studies similarly reported on verbalization in the learning of spatial information (e.g. Gwinn et al., 2002; Pazzaglia & De Beni, 2001). Verbal processes may help to abstract the features of landmarks and scenes, as implied by the finding that after verbalization, memory for nonverbal information such as faces, voices or tastes was better organized and easier to recognize (e.g. Itoh, 2005; Lloyd-Jones, Brandimonte, & Bäuml, 2008). The spatial component is also found to be critical for the processing of landmark knowledge. Although some studies showed that people used landmarks to make spatial judgments in navigation (e.g. Blajenkova et al., 2005; Gwinn et al., 2002), it remained unclear whether landmark knowledge is spatially processed in working memory. Our results show that it is. Verbal processes may lead to abstraction of the features of landmarks and scenes for identification, and spatial processes to the comprehension and use of metric information such as distances and directions.

In contrast, poor-SOD people’s performance on scene recognition did not decrease when spatially disrupted, indicating that they did not process landmark knowledge spatially, as good-SOD people did. This finding is consistent with Blajenkova et al.’s (2005) findings, which showed that only survey-type people used knowledge about landmarks for spatial updating in navigation. In other words, good-SOD people may tend to think of landmarks spatially in terms of geometry or in relation to other landmarks, and grasp their locations in a common frame of reference, which probably leads to the acquisition of accurate survey knowledge as discussed below.

**Working memory in the acquisition of route knowledge**

On the route-choice task, good-SOD people did poorly when they were verbally and spatially disrupted, showing that the verbal and spatial components of working memory are involved in the acquisition of route knowledge. Furthermore, performance at chance level in the spatial interference condition implies a particularly strong involvement of spatial working memory for good-SOD people. Concerning the verbal processing, routes can be described verbally (e.g. ‘Go straight on Main Street and turn left when you see a post office’), by organizing sequences of landmarks and actions at decision points.

Similarly, poor-SOD people’s performance on route choice decreased when verbally and spatially disrupted. But they also did poorly when visually disrupted, a finding that was not observed for good-SOD people. That is, poor-SOD people, unlike good-SOD people, encoded knowledge about routes visually. In addition, performance at chance level in the verbal and visual interference conditions implies a particularly strong involvement of verbal and visual working memory for poor-SOD people. This result is consistent with Aginsky et al.’s (1997) findings, which showed that both survey-type and non-survey people employed visual strategies in route learning, but only survey-type people used spatial strategies in which decision points were integrated into survey-type representations.

Concerning the spatial processing of route knowledge, poor-SOD people’s performance decreased in the spatial interference condition, but their sketch maps were not correctly drawn. That is, although the spatial component of working memory was somehow involved in the encoding of route knowledge, they did not acquire accurate knowledge about spatial properties of the routes, such as the directions of major turns.

**Working memory in the acquisition of survey knowledge**

On the map-sketching task, good-SOD people did poorly when they were verbally, visually and spatially disrupted, showing that the three components of working memory all
played critical roles in the acquisition of survey knowledge. Because the acquisition of survey knowledge requires separate landmarks and routes being spatially interrelated with each other, the involvement of the spatial component should be important. Noteworthy is the involvement of the visual component. It might suggest that in the process of integrating landmark and route knowledge into survey knowledge, ‘mental maps’ are in some sense visually scrutinized, to comprehend the relationships between landmarks and routes. In fact, our good-SOD participants tended to respond positively to the SOD item ‘I usually envision a two-dimensional map in mind when learning a novel route’.

In the literature, large individual differences have been observed for tasks concerning survey knowledge, instead of landmark or route knowledge (e.g. Ishikawa & Montello, 2006; Blajenkova et al., 2005). This was also confirmed in our study. In the control condition, good- and poor-SOD people performed equivalently on scene recognition and route choice, but poor-SOD people did much worse on map sketching. In the good-SOD group, 11 of 16 participants drew correct sketch maps, while only 5 of 16 participants did in the poor-SOD group (Table 2).

The fact that good-SOD people encode landmark and route knowledge spatially, as well as verbally, may explain why they acquire accurate survey knowledge. Because of the spatial processing or of the effect of dual coding (Paivio, 1991), these people can integrate separate landmarks and routes into a common frame of reference. In contrast, poor-SOD people fail to encode landmarks spatially and rely on visual encoding of routes unlike good-SOD people, which leads to lack of spatial information about landmarks and routes, and thus were unable to integrate them spatially into accurate survey knowledge.

We here note possible differences between the formats of internal and external representations. That is, people who drew accurate sketch maps did not necessarily store the knowledge of routes in map-like format; they may, for example, have represented their knowledge externally in map form that was internally stored in verbal format. The main focus of this study is on the encoding processes of spatial information.

Model for the processing of spatial knowledge

On the basis of our results, we propose a model for explaining how working memory is involved in the acquisition of different types of spatial knowledge, for good- and poor-SOD people (Figure 4). For good-SOD people, information about landmarks and routes is processed in the verbal and spatial components of working memory. In other words, landmark knowledge and route knowledge are verbally and spatially encoded into long-term memory. In the verbal processing, landmarks are remembered with their features being abstracted, and routes are learned in terms of sequences of landmarks and actions at decision points. In the spatial processing, spatial information about landmarks and routes, such as locations, directions or distances, are encoded into long-term memory, so that it can be retrieved and used when necessary.

Knowledge about landmarks and routes thus acquired is integrated into survey knowledge being processed in all three components of working memory. As landmarks and routes are encoded verbally and spatially, the verbal and spatial components are involved in their integration. The integration is also processed with the support of visual working memory, which may help to integrate spatial relations between landmarks and routes. This issue needs further investigation, however.

For poor-SOD people, information about landmarks is processed in the verbal component of working memory, and information about routes is processed in the three components of working memory. In stark contrast to the processing by good-SOD people are the lack of spatial processing of landmark knowledge and the existence of visual processing of route knowledge. Because landmarks are not spatially encoded, their spatial (or metric) information, such as distances or directions, is not readily available, hence the involvement of the visual component of working memory in the processing of route knowledge. Because of the lack of spatial processing and the reliance on visual processing, the integration of landmarks and routes into survey knowledge cannot be fully achieved by poor-SOD people, as done by good-SOD people.

Figure 4. Model of spatial knowledge acquisition. Black arrows indicate the encoding processes for the three types of spatial knowledge; white arrows indicate the integration of landmark and route knowledge into survey knowledge. For good-SOD people, information about landmarks and routes is processed in the verbal and spatial components of working memory. Knowledge thus acquired is integrated into survey knowledge being processed in all three components of working memory. In contrast, for poor-SOD people, landmark knowledge is not spatially processed and route knowledge is visually processed.
As well as our results, this model accounts for the results from the two past studies of the relationship between working memory and spatial knowledge acquisition (Garden et al., 2002; Meilinger et al., 2008). Garden et al. (2002) found that the visuospatial sketchpad was involved only for survey-type participants. According to our model, their result is paraphrased more specifically that the spatial subcomponent of the visuospatial sketchpad was involved in their highspatial participants. Meilinger et al. (2008) found the involvement of the spatial and verbal components of working memory, but not the visual component. According to our model, the visual component is involved in the acquisition of route knowledge for poor-SOD people, and in the acquisition of survey knowledge for good-SOD people. A possible reason for the discrepancy is that Meilinger et al.’s participants had a relatively good SOD, and their route-following task in the virtual environment tapped into landmark and route knowledge.

Finally, in this research, routes were presented to participants as videos. Past research showed that differences in the sources of information affected internal representations of acquired spatial knowledge (Hegarty et al., 2006). For example, in viewing videos, as contrasted to direct navigation in the environment, participants are not provided with kinesthetic or vestibular information, which has been shown to contribute to spatial updating (e.g. Klatzky, Loomis, Beall, Chance, & Golledge, 1998). Also, in contrast to the real environment, which surrounds and is larger than humans, videos are shown as flat pictures at a smaller scale and restrict peripheral vision (Sholl, 1996). It is thus an important research question for further study whether processing of spatial information in working memory differs when information about space is acquired from different sources of information. Similarly, possible differences between active versus passive navigation is another important topic (e.g. Bakdash, Linkenauger, & Profitt, 2008). With continued research on these issues, the findings from this study provide insights into the question about individual differences in spatial cognition, which is an important and indispensable aspect of people’s daily activities.

REFERENCES
APPENDIX
The six additional questions about SOD:
Q16. I can usually memorize a place even if I have been there only once.

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Q17. When I visit a new place, I often think that I have been there before.
Q18. I usually memorize salient buildings or signboards at intersections when learning a route.
Q19. I am very good at learning the layout of an environment.
Q20. I cannot recall which direction to turn until I come to the intersection.
Q21. I usually envision a two-dimensional map in mind when learning a novel route.